

## Code Optimization on Kepler GPUs and Xeon Phi

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Kepler GTX Titan Black and Kepler Tesla K40 are still the best GPUs for high performance computing, although Maxwell GPUs such as GTX 980 are available in the market. Hence, we measure the performance of our lattice QCD codes using the Kepler GPUs. We also upgrade our code to use the latest CPS (Columbia Physics System) library along with the most recent QUDA (QCD CUDA) library for lattice QCD. These new libraries improve the performance of our conjugate gradient (CG) inverter so that it runs twice faster than before. We also investigate the performance of Xeon Phi 7120P coprocessor. It has similar computing power with the Kepler GPUs in principle. However, its performance for our CG code is significantly inferior to that of the GTX Titan Black GPUs at present.

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## 1. Introduction

We reported the performance of NVIDIA Kepler GTX Titan in Lattice 2013 [1]. Since Lattice 2013, NVIDIA has released new Kepler GPUs such as GTX Titan Black and Tesla K40, which show even better computing performance than Maxwell GPUs. We measure the performance of GTX Titan Black and Tesla K40m. We also upgrade our code by adopting QUDA (library for QCD on GPU) so that we can get a better performance from the Kepler GPUs.

We reported the performance of single Intel Xeon Phi 5110P card in Lattice 2013 [1]. In 2014, we perform the same test on a multiple Xeon Phi 7120P system. Here we report its performance. We also find a problem on a parallel computing system with multiple Xeon Phi 7120P cards connected via infiniband network. We will describe this in detail in Section 4.

## 2. GTX Titan Black

Architecture	Fermi	Kepler				Maxwell
	GTX 580	Tesla K20X	Tesla K40	GTX 780Ti	GTX TITAN Black	GTX 980
SP TFLOPS	1.58	3.95	4.29	5.04	5.1	4.61
DP TFLOPS	0.20	1.31	1.43	0.21	1.3	0.14
Memory Size (GB)	1.5	6	12	3	6	4
Memory Bandwidth (GB/sec)	192.4	250	288	336	336	224
L2 cache (MB)	7.7	1.5	1.5	1.5	1.5	2
Price (USD)	N/A	3,000	4,000	800	1,300	700

Table 1: chip and memory specifications of recent NVIDIA GPUs

In Table 1, we present chip and memory specification of high-end NVIDIA GPUs. Although Maxwell GPUs are cheap, they have very poor double precision performance and lower memory bandwidth than GTX Titan Black and Tesla K40. Hence, GTX Titan Black and Tesla K40 are still the best GPUs for high performance computing at present.

In Fig. 1, we present the performance of our conjugate gradient (CG) inverter by Fermi GTX 580 and Kepler GTX Titan Black. In the CG code, we use mixed precision algorithm, in which most of the calculations are performed in single precision. In this plot, two-GPU data points use the PCI bus, and four-GPU data points use the PCI bus and infiniband network through MPI. Hence, this plot shows that GTX Titan Black outperforms GTX 580 by a factor of 1.3–1.6 regardless of the network environment. Details of the plot are summarized in Table 2.

The performance includes data transfer between GPUs. While GTX 580 supports PCI express 2.0, GTX Titan Black supports PCI express 3.0 which provides twice larger bandwidth than the former. We guess that the performance increase of GTX Titan Black with two GPUs comes in part from the speed-up in the PCI bus.

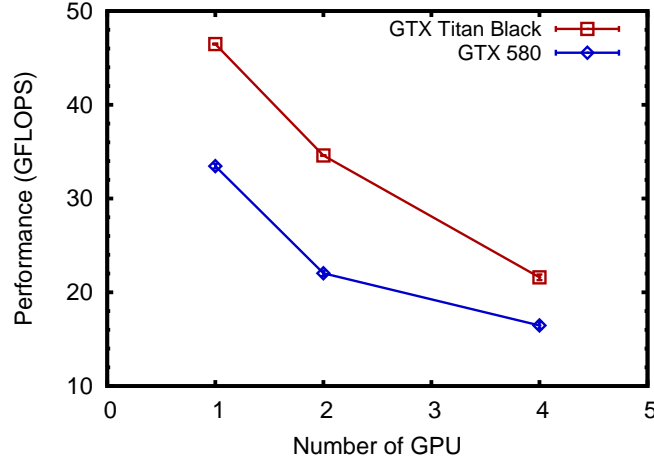


Figure 1: CG performance in the unit of giga flops. The data are obtained by running the CG code 10 times on the  $20^3 \times 64$  MILC asqtad lattice at  $a \cong 0.12$  fm.

# of GPU	Performance (GFLOPS )		Ratio
	GTX 580	GTX Titan Black	
1	33.46(26)	46.48(6)	1.39(1)
2	22.03(30)	34.59(2)	1.57(2)
4	16.47(36)	21.60(30)	1.31(1)

Table 2: Results of CG performance in Fig. 1. The ratio is taken between GTX Titan Black and GTX 580.

Figure 2 shows the performance of the one-color four fermion operator calculation of Eq. (2.1) in our non-perturbative renormalization (NPR) production code on GTX 580 and GTX Titan Black.

$$\begin{aligned}
O_{i,l}^{f_1 f_2 f_3 f_4}(z) = & \overline{\chi}_{i;c_1}^{f_1}(z_A) (\gamma_{S_1} \otimes \xi_{F_1})_{AB} \chi_{i;c_2}^{f_2}(z_B) \times \overline{\chi}_{i;c_3}^{f_3}(z_C) (\gamma_{S_2} \otimes \xi_{F_2})_{CD} \chi_{i;c_4}^{f_4}(z_D) \\
& \times [U_{i;AD}]_{c_1 c_4}(z) [U_{i;CB}]_{c_3 c_2}(z)
\end{aligned} \tag{2.1}$$

where  $\chi$  and  $\overline{\chi}$  are staggered quark fields, and  $U_{i;AD}(z)$  is the gauge link averaged over all the shortest paths between  $A$  and  $D$  at the hypercubic coordinate  $z$ . Here,  $S_1$  and  $S_2$  represent the spins of the bilinears, and  $F_1$  and  $F_2$  the tastes of the bilinears. This part of the NPR code occupies about 98% of the total running time. Hence, this is the most dominant part in the NPR production code. All of the calculation in the NPR code is done in double precision. Therefore, we can measure the performance of the GPUs in double precision floating point calculation using the NPR code. As one can see in Fig. 2, the double precision performance is quite flat regardless of the network environment because we exclude the network communication part (which is negligibly small compared with the floating point calculation of the GPUs) from this estimate.

We expect that GTX Titan Black, in principle, outperforms GTX 580 by a factor of  $1.3/0.2 \approx 6.5$  in the double precision calculation. However, we obtain only 1.5 times throughput rate in practice as one can see in Table 3. The main reason is that the memory bandwidth increase only by a factor of 1.75 in the case of GTX Titan Black. Therefore, the NPR code can not fetch the data fast enough to use the full capability of the double precision calculation of GTX Titan Black.

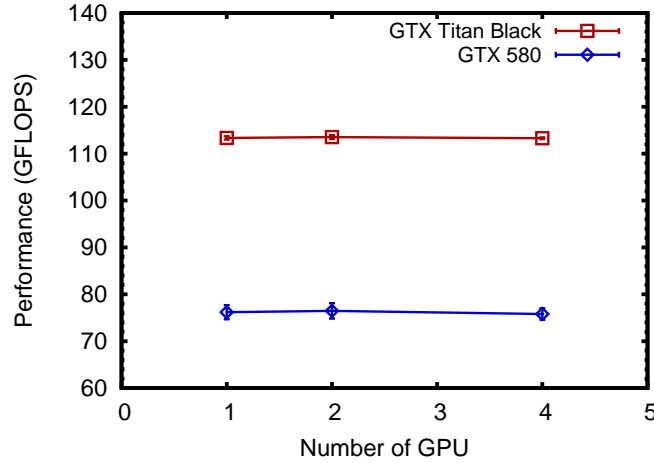


Figure 2: Performance of one-color four fermion operator part of the NPR production code in the unit of giga flops. The data are obtained by taking the average of 10 times running the code on the  $20^3 \times 64$  MILC asqtad lattice at  $a \cong 0.12$  fm.

# of GPU	Performance (GFLOPS )		Ratio
	GTX 580	GTX Titan Black	
1	76.19(150)	113.36(35)	1.49(2)
2	76.47(165)	113.53(42)	1.48(3)
4	75.80(122)	113.29(19)	1.49(2)

Table 3: Results of NPR code performance in Fig. 2. The ratio is taken between GTX Titan Black and GTX 580.

Our conundrum is that we expect to obtain still a gain of 1.75 (= the maximum saturation limit of memory bandwidth) in the NPR code but have gotten only the gain of 1.5 in practice. This needs further investigation in near future.

To achieve the highest performance of the GTX Titan Black and other Kepler GPUs, it is necessary to optimize the code as follows: (1) tune thread and block scheduling, (2) increase CGMA (compute to global memory access) ratio, (3) improve memory usage by new features such as read-only data cache and warp shuffle, and (4) reduce unwanted communications between GPUs and CPUs by applying direct parallelism and GPU Direct [1].

### 3. CPS & QUDA

Recently we have upgraded the CPS (Columbia Physics System) library from version 4.2 to version 5.0. The main advantage of the upgrade is that it allows us to use the QUDA library which is a library for lattice QCD based on CUDA [2]. The QUDA library that we use for the performance test and production jobs is version 0.5.1. The QUDA library provides highly optimized version of the CG (conjugate gradient) inverter and its variations such as BiCG (bi-conjugate gradient) and PCG (preconditioned conjugate gradient) for the Nvidia GPUs. At present, it is designed to give the highest performance for the Kepler family of Nvidia GPUs. In addition, it also finds the

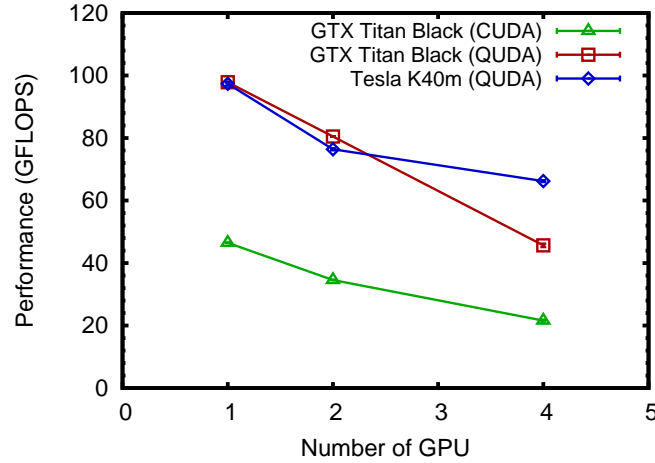


Figure 3: CG performance in the unit of giga flops. Here CUDA means the old version 4.2 of CPS library, and QUDA means the new version 5.0 of CPS library compiled with QUDA library. We use the same method as in Fig. 1.

optimized running parameters for the system, dynamically and automatically, for any given system environment. It also supports the mixed precision algorithm for the CG inverter.

The latest CPS library (version 5.0) does not have an interface to call the CG inverter for staggered quarks in the QUDA library. Hence, recently we have added this interface to the CPS library to run the staggered CG inverter of the QUDA library.

In Fig. 3, we present the performance of the new CPS library (version 5.0) compiled with the QUDA (version 0.5.1) library (brown square symbols), and that (green triangle symbols) of the old CPS library (version 4.2) compiled with the CUDA library (version 6.0). In the case of the single GPU test, the new CPS library with QUDA accelerate the speed of the CG inverter by a factor of 2.1. In the case of two GPU test, the results of GTX Titan Black is obtained using the PCI bus (bandwidth = 16 giga bytes per second), but that of Tesla K40m is obtained using the infiniband FDR (fourteen data rate) network (bandwidth = 56 giga bits per second). In the case of four GPU test, the results of GTX Titan Black is obtained using the infiniband QDR (quad data rate) network (bandwidth = 32 giga bits per second), and that of Tesla K40m is obtained using the infiniband FDR network. In Table 4, we summarize details of Fig. 3. This shows that the gain in the performance of the CG inverter is 2.11 even in the infiniband network environment.

# of GPU	Performance (GFLOPS )			Ratio
	Titan Black (old)	Titan Black (new)	K40m (new)	
1	46.48(6)	97.86(21)	97.37(60)	1 : 2.11 : 2.09
2	34.59(2)	80.48(6)	76.40(32)	1 : 2.33 : 2.21
4	21.60(30)	45.66(55)	66.24(30)	1 : 2.11 : 3.07

Table 4: Results of CG performance in Fig. 3.

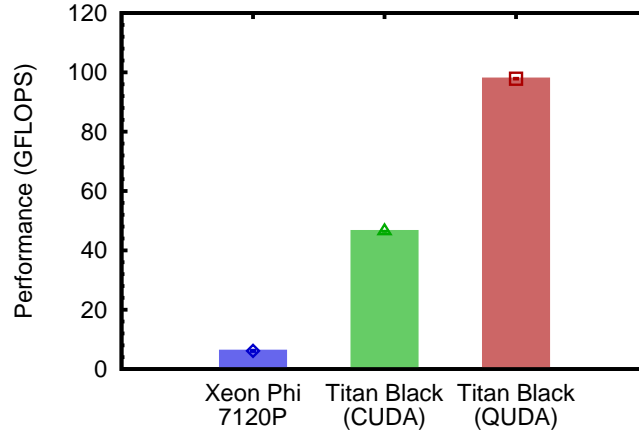


Figure 4: CG performance in the unit of giga flops. We use the same method as in Fig. 1.

#### 4. Xeon Phi Coprocessor

In Table 5, we present the specification of Xeon Phi coprocessors and compare it with NVIDIA Kepler GPUs. A Xeon Phi coprocessor has as much core performance and as large memory bandwidth as the high-end NVIDIA Kepler GPUs. Hence, we expect that Xeon Phi can give, in principle, the same performance as GTX Titan Black or Tesla K40.

	Intel Xeon Phi		NVIDIA GPU	
	5110P	7120P	Tesla K40	GTX Titan Black
# of Cores	60	61	2880	2880
Core Clock (MHz)	1053	1333	745	889
SP TFLOPS	2.02	2.44	4.29	5.1
DP TFLOPS	1.01	1.22	1.43	1.3
Memory Size (GB)	8	16	12	6
Mem. Bandwidth (GB/s)	320	352	288	336

Table 5: specification comparison between Intel Xeon Phi coprocessors and NVIDIA Kepler GPUs

The Xeon Phi coprocessor supports 512 bit SIMD (single instruction multiple data) operations so that it can compute 16 single precision calculations simultaneously. Hence, the actual performance of Xeon Phi system highly depends on the vectorization of the code. Figure 4 shows the performance of the CG code on Xeon Phi 7120P and GTX Titan Black. Results are summarized in Table 6. Here, note that we have not done the proper vectorization of our CG code for Xeon Phi 7120P yet. In this case, we report that the performance of our CG code for Xeon Phi 7120P is much less than that for GTX Titan Black by a factor of 1/16.

We find two major reasons for the poor performance of Xeon Phi. First, our code is not fully vectorized to use 512 bit SIMD operations through the automatic vectorization option of the Intel compiler. To do this, we need to modify the code such that the code feeds the data in the unit of 16 floating point numbers to the cores. In order to achieve this properly, we may have to write

Device	Performance (GFLOPS )	Ratio
Xeon Phi 7120P	6.14(30)	1
GTX Titan Black (CUDA)	46.48(6)	7.57(36)
GTX Titan Black (QUDA)	97.86(21)	15.94(74)

Table 6: Results of CG performance in Fig. 4.

the code in the assembly language. Second, we assign 200 MPI processes per Xeon Phi, and the performance of each core decreases due to a big loss in the data distribution speed of Xeon Phi. Part of this problem comes from the poor software support on the MPI library. Hence, we plan to use OpenMP to distribute the data to the cores because the OpenMP library supports the shared memory so that it can alleviate the bottleneck problem in data distribution somewhat. There has been a report on the success in implementing OpenMP and SIMD vectorization to achieve as high performance as Tesla K20m in Ref. [3].

We also tested the scalability of the multiple Xeon Phi system. If we use multiple Xeon Phi 7120Ps through MPI, the performance of the system drops abruptly, and sometimes the system even crashes completely. We guess that there must be some bug of the native method on the multiple Xeon Phi system with the infiniband network. Hence, we plan to investigate the offload method.

## 5. Conclusion

GTX Titan Black improves the performance of our lattice QCD GPU codes by 40% ~ 60% compared with GTX 580 without any optimization specific to Kepler GPUs. On top of that, we achieved 2.1 times more performance by adopting the latest CPS library with the QUDA library for staggered quarks. Meanwhile, in order to obtain a comparable performance from Xeon Phi system, we should optimize our code further using the vectorization and OpenMP, which needs further investigation in near future.

## 6. Acknowledgement

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